NASA CONTRACTOR REPORT

NASA CR-164

NASA CR-164

N65 15883

(ACCESSION NUMBER) (THRU)

19 1

(PAGES) (CODE)

12

(CATEGORY)

GPO PRICE $ ________

OTS PRICE(S) $ ________

INSTABILITIES IN THE FLOW OF BOILING LIQUID

by A. H. Stenning and T. N. Veziroglu

Prepared under Grant No. NsG-424 *by*
UNIVERSITY OF MIAMI
Coral Gables, Fla.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1965

NASA CR-164

INSTABILITIES IN THE FLOW OF BOILING LIQUID

By A. H. Stenning and T. N. Veziroglu

Prepared under Grant No. NsG-424 by
UNIVERSITY OF MIAMI
Coral Gables, Fla.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $1.00

INSTABILITIES IN THE FLOW OF BOILING LIQUID

By A. H. Stenning and T. N. Veziroglu

During the third six-monthly period of the project, two-component two-phase flow experiments using air and water have been completed, and one-component two-phase flow experiments using Freon-11 have been started. Since they pertain to a concluded phase of the work, the results of the experimental and analytical program on two-component two-phase flow have been presented as a separate report [1]. The first series of experiments using the Freon-11 apparatus were completed during the summer of 1964. A second series of experiments is now in progress after some changes to the apparatus which resulted in a reduction of permanent inlet pressure drop and the inlet inertia inherent to the system geometry. The results to-date indicate that a one-component two-phase horizontal flow system is more stable than a two-component two-phase downward flow system, probably due to the increase in slip and the stabilizing effect of convective heat transfer. During Freon-11 experiments, two new types of flow instability, termed "Thermal Two-Phase Flow Oscillations" and "Pressure Drop Two-Phase Flow Oscillations" have been encountered. These oscillations are characterized by much larger periods than those of "regular" two-phase flow oscillations; e.g. 60 seconds and 30 seconds per cycle respectively as compared with about 3 seconds per cycle for regular oscillations. Thermal oscillations give rise to large pressure oscillations, and could therefore be more dangerous.

As the results of two-phase two-component air-water investigation have already been reported, the present report will be confined to the preliminary results of the Freon-11 experiments which are still in progress.

FREON-11 APPARATUS

A general description of the Freon-11 Apparatus was presented earlier [2] when it was being built. However, since then some modifications and improvements have been incorporated in the apparatus. The test section (Fig. 1) consists of a surge tank, an inlet valve, a heater, and an exit valve with some tubing in between to facilitate various connections. All the tubing in the system, including the heater, is made of nichrome with 3/16 inch O.D. and 0.1475 inch I.D. The heater tube, 37 1/2 inches long, itself is used as the electrical resistance for providing heat input. D. C. voltage is applied at the ends of the heater tube, and power input up to 5 k. w. can be obtained with a maximum current of 200 amperes. The voltage across the heater is adjusted by means of a regulator to obtain the desired heat input. In order to reduce the heat losses to a minimum, a vacuum jacket is built around the heater, which contains a guard heater and a radiation guard. The vacuum jacket is connected to a vacuum pump to evacuate air and other gases. (Heat input calculated from the enthalpy increase of the flow was within 3 per cent of that found from electrical measurements, indicating an efficient thermal insulation). At the inlet side of the heater a sight glass tube is included in the system to make sure that no evaporation starts in the liquid before reaching the heater. The surge tank, which provides a constant overall pressure drop across the system, is made of clear lucite so that the liquid level is visible. It is provided with a bicycle type check valve for pumping in air as needed, since it was found out that the trapped air would flow out through the system in between the experiments and be replaced by Freon-11 vapor which in turn would condense during the experiments as pressures were increased. Two flow-through copper-constantan thermocouples were inserted into the system before and after the heater to measure the temperatures of Freon-11. Five copper-constantan thermocouples were fixed to the outer wall of the heater for measuring heater temperatures. They were electrically insulated from the heater by means of 0.0015 inch thick mica flakes. Three bourdon tube type Heise pressure gages and two strain gage type pressure transducers were installed in the test section to measure the pressures at various stations across the system, and sense the pressure oscillations. The pressure oscillations were recorded on a Sanborn chart recorder.

The experimental set-up included a Freon-11 container at the upstream side of the test section, and a Freon-11 recovery system at the downstream side. The Freon-11 container has a volume of 4 ft^3 and is made of stainless-steel to withstand pressures up to 150 p.s.i.g. During the experiments Freon-11 in the container is pressurized by means of high pressure nitrogen and a constant pressure regulating valve in order to obtain a steady and continuous flow into the surge tank, via a filter, a micrometer control valve and a rotameter. Superheated Freon-11 or a mixture of saturated Freon-11 vapor and liquid leaving the test section is led into the recovery system. This system is essentially a heat exchanger where Freon-11 is condensed by making it run through a helical aluminum tube around which refrigerated brine at 32°F. circulates. It is enabling us to recover 80 to 90 per cent of the Freon-11 used.

During the first series of experiments the surge tank was not installed. Consequently, the supply tank acted as the surge tank, providing a constant pressure, and the test section started from the Freon-11 tank.

EXPERIMENTAL PROCEDURE

In experiments for determining the onset of oscillations and the influence of the parameters affecting the oscillations, first, liquid Freon-11 was run through the system with the inlet valve partly closed and the exit valve fully open, after pressurizing the Freon-11 in the container up to 50 to 60 p.s.i.g. by means of Nitrogen gas. The regulator valve kept the tank pressure constant within ± 0.1 p.s.i. during the experiments. Then the heater was started at a relatively low power level (about 100 watts). Its power was then increased to a predetermined test level by 50 watt increments. After each change in power, about 10 minutes was allowed to elapse before the next change. This procedure prevented unwanted transient instabilities. During the heater power level increases, the Freon-11 flow rate was increased as required by adjusting the control valve so that the system was always operating within the stable zone at steady state. After the test power level was reached, the exit valve was set so as to provide a predetermined exit pressure drop and the control valve was set to provide a predetermined flow rate. Then the inlet valve was slowly opened till the onset of two phase flow oscillations was noticed. These oscillations could be observed from the periodic motion of the pressure gage pointers and also from the pressure recordings. At the stability boundary the room temperature, barometric pressure, Freon-11 mass flow rate, heater voltage and current, and pressure and temperature (thermocouple) readings at various stations along the test system were recorded. Since the earlier experiments indicated that there was no noticeable hysteresis effect, the stability boundary was always reached from the stable zone as this procedure resulted in some savings in time and Freon-11. After taking the readings, the flow rate was slightly reduced by closing down on the control valve. This caused the system to operate in the unstable zone. At this stage, pressure recordings were made for more accurate frequency calculations. Figs. 2(a) and (b) show the pressure recordings at the stability boundary and within the unstable region for one experiment.

For each stability boundary experiment some heat transfer measurements were carried out to determine the fraction of heat transfer independent of flow rate. During each of these experiments, all the settings with the exception of the control valve setting were kept as they were at the stability boundary. By increasing the control valve opening, the Freon-11 flow rate was increased, and the corresponding flow, power, pressure and temperature readings were taken.

The above mentioned procedure was repeated for various flow rates, exit valve settings and heater power levels. During the experiments the system geometry has been changed once. The earlier experiments were carried out without the surge tank; and present experiments are being carried out with the surge tank included.

During the course of experiments, in addition to the "regular" two phase flow instability, two distinctly different types of instability have been discovered. Some preliminary tests have been carried out to obtain an understanding of these new instabilities. After the present series of experiments on regular two-phase flow oscillations are completed, the above mentioned oscillations will be systematically investigated.

Experimental Results

Analyses made earlier [3] indicate that the parameters affecting the onset of one-component two phase flow oscillations are overall density ratio, heat fraction expended in removing subcooling, heat transfer fraction independent of mass flow rate, system geometry defined as dimensionless inlet ducting length and exit ducting length, dynamic pressure, inlet pressure drop fraction and other pressure drop fractions across the heater and at the exit. Because of the interdependence of the parameters, it was not possible to keep all but two constant and investigate their relationship. Under the circumstances, in order to reduce the number of variables, first overall density ratios ($1/r_{exit}$) were plotted against the heat fraction used in removing subcooling (c) for all of the stability onset experiments for a given geometry (Fig. 3). As seen from the figure, points corresponding to a certain power level of the heater fall on a smooth curve. These curves are in fact operating curves for the system. Then the points corresponding to a constant c are selected from Figure 3, and the inlet fraction of pressure drop (y) and the overall density ratio ($1/r_{exit}$) are determined for each such point. In order to keep c constant, some of the points have been found by interpolation between the two nearest onset points. The results are plotted for various values of c as seen in Fig. 4. The region above each curve is stable, and below unstable. From Figure 4, it can be seen that (a) increase in overall density ratio decreases stability; (b) increase in inlet fraction of pressure drop increases stability; and (c) increase in subcooling decreases stability. Experiments also showed that for a given subcooling the corresponding stable points had higher inlet pressure drop fractions than that of the onset point, and the unstable points had lower inlet pressure drop fractions. All of the above observations were indicated by earlier analog computer studies of similar systems.

If we compare the results of these one-component two-phase horizontal flow experiments with those of two-component two-phase downward flow experiments [1], it becomes clear that a one-component two-phase flow is much more stable. In other words, a smaller inlet fraction y of pressure drop is required to stabilize a one-component two-phase flow system, or the system will tolerate much higher density ratios for a given y. This is probably caused by dependence of heat transfer on the mass flow rate, and slip, both of which tend to make a system more stable. A qualitative comparison awaits a detailed computer study.

As mentioned earlier, two new types of two phase flow oscillations were encountered during the experiments. In order to distinguish them from each other, one of the new types — which seems to be caused by film boiling heat flux characteristics — will be called "Thermal Two-Phase Flow Oscillations", and the other type — which seems to be caused by boiling flow pressure drop characteristics — will be called "Pressure Drop Two-Phase Flow Oscillations". For the same reason, the regular two phase flow oscillations could appropriately be called "Density Wave Two-Phase Flow Oscillations" since they are caused primarily by the interaction of density and flow rate changes.

We can enumerate the initial observations about and the distinguishing features of the new types of oscillations as follows:

I. Thermal Two-Phase Flow Oscillations:

a) They seem to be made by the superimposition of two different waves; one having a relatively low frequency, and the other having higher frequency and starting and dying off at regular intervals. Figure 5 shows a pressure recording of these oscillations. It seems that the high frequency component of these oscillations consists of density wave oscillations.

b) There are large variations (up to 40%) in flow rate during each cycle of the oscillation.

c) Pressure oscillations are very fierce during the part of the cycle when high frequency waves are prominent. Pressure amplitudes of more than 100 p.s.i.g. were observed when overall system pressure drops were only 50 p.s.i.g. As a result, two Heise pressure gages were damaged. It seems that this type of oscillations could be the most dangerous of the three.

d) They start at about the same flow conditions as the density wave oscillations. If the system is made more unstable, by either decreasing the inlet pressure drop or decreasing the flow rate (i.e., increasing the overall density ratio), the thermal oscillations will be replaced by the density wave oscillations. At this stage, the amplitude of pressure oscillations are much less than those produced by the thermal instability. It seems that the thermal two-phase flow oscillations are triggered by density wave oscillations in first place, and they can also be eliminated by increasing the intensity of density wave two-phase flow oscillations.

e) They are only observed at relatively high heat transfer rates (e.g., for heat fluxes more than 17,000 B.T.U./hr.ft.^{2}), although density wave oscillations could be started with lower heat transfer rates too.

f) During the thermal oscillations the exit end of the heater operates in the film boiling region. There are large amplitude (e.g., 100°F.) wall temperature oscillations (Fig. 6), in phase with flow and pressure oscillations, at the exit end of the heater. (No wall temperature oscillations have been observed in the case of density wave oscillations, and in the case of pressure drop two-phase flow oscillations the maximum change in wall temperature during a cycle was not more than 1 or 2°F.)

II. Pressure Drop Two-Phase Flow Oscillations:

a) They have frequencies between those of density wave oscillations and thermal oscillations. For example, during our experiments, the frequencies of the density wave, thermal and pressure drop type oscillations were of the order of 0.3 c.p.s., 0.015 c.p.s., and 0.03 c.p.s. respectively.

b) In general, the amplitude of pressure oscillations are not as large as those of the two other types of instability (Fig. 7).

c) They happen in a bounded region of overall density ratios, outside of which (i.e., for density ratios lower than the lower boundary density ratio and higher than the higher boundary density ratio) the system is stable for this type of oscillations. They seem to occur whenever the pressure drop versus flow curve for the heater has a negative slope at the operating point.

d) This bounded region can be within the stable zone of density wave (and for that matter, thermal type) oscillations. In other words, pressure drop oscillations can take place at lower density ratios than the other types of two-phase flow oscillations.

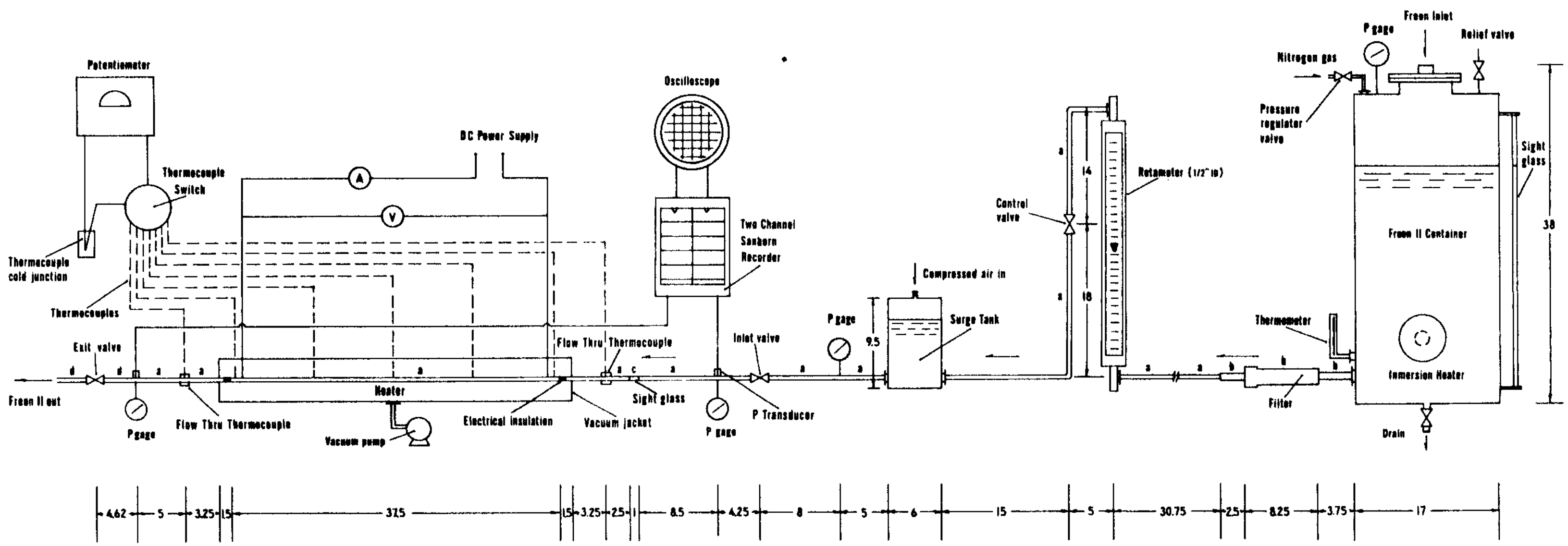
e) They can be stopped by increasing the inlet pressure drop, just as in the case of other types of two-phase flow instabilities.

REFERENCES

1. Stenning, A. H. and Veziroglu, T. N.: "Oscillations in Two-Phase Two-Component Flow", NASA Grant NsG-424 Report No. 4, October 1964.

2. Stenning, A. H. and Veziroglu, T. N.: "Semi-Annual Status Report on Boiling Flow Instability", NASA Grant NsG-424 Report No. 2, November 1963.

3. Stenning, A. H. and Veziroglu, T. N.: "Semi-Annual Status Report on Boiling Flow Instability", NASA Grant NsG-424 Report No. 3, May 1964.



Inside Tube Dia	
a	0.1475
b	0.5
c	0.155
d	0.185

Note: All dimensions in inches.

FIG. I.– SCHEMATIC DIAGRAM OF EXPERIMENTAL SET-UP FOR ONE-COMPONENT TWO-PHASE FLOW INSTABILITY [FREON-II APPARATUS]

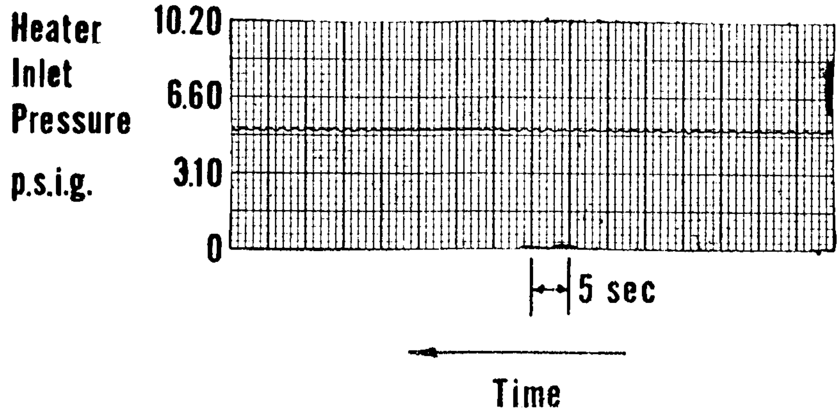


FIG.2(a).—A PRESSURE RECORDING AT STABILITY BOUNDARY

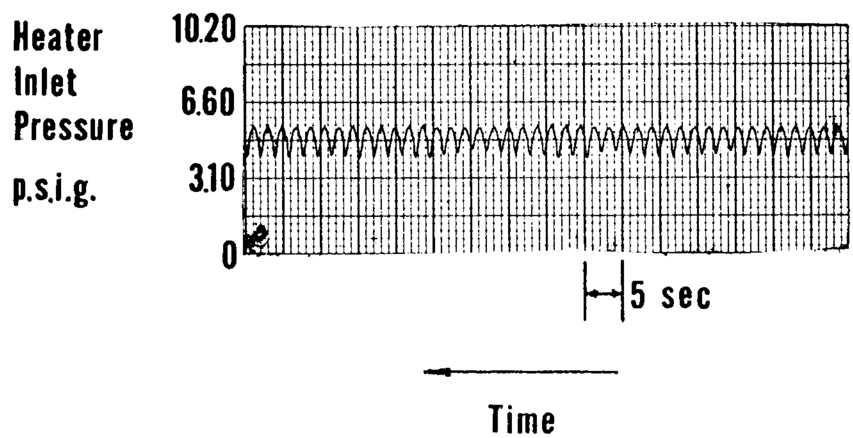


FIG.2(b).—A PRESSURE RECORDING IN UNSTABLE REGION

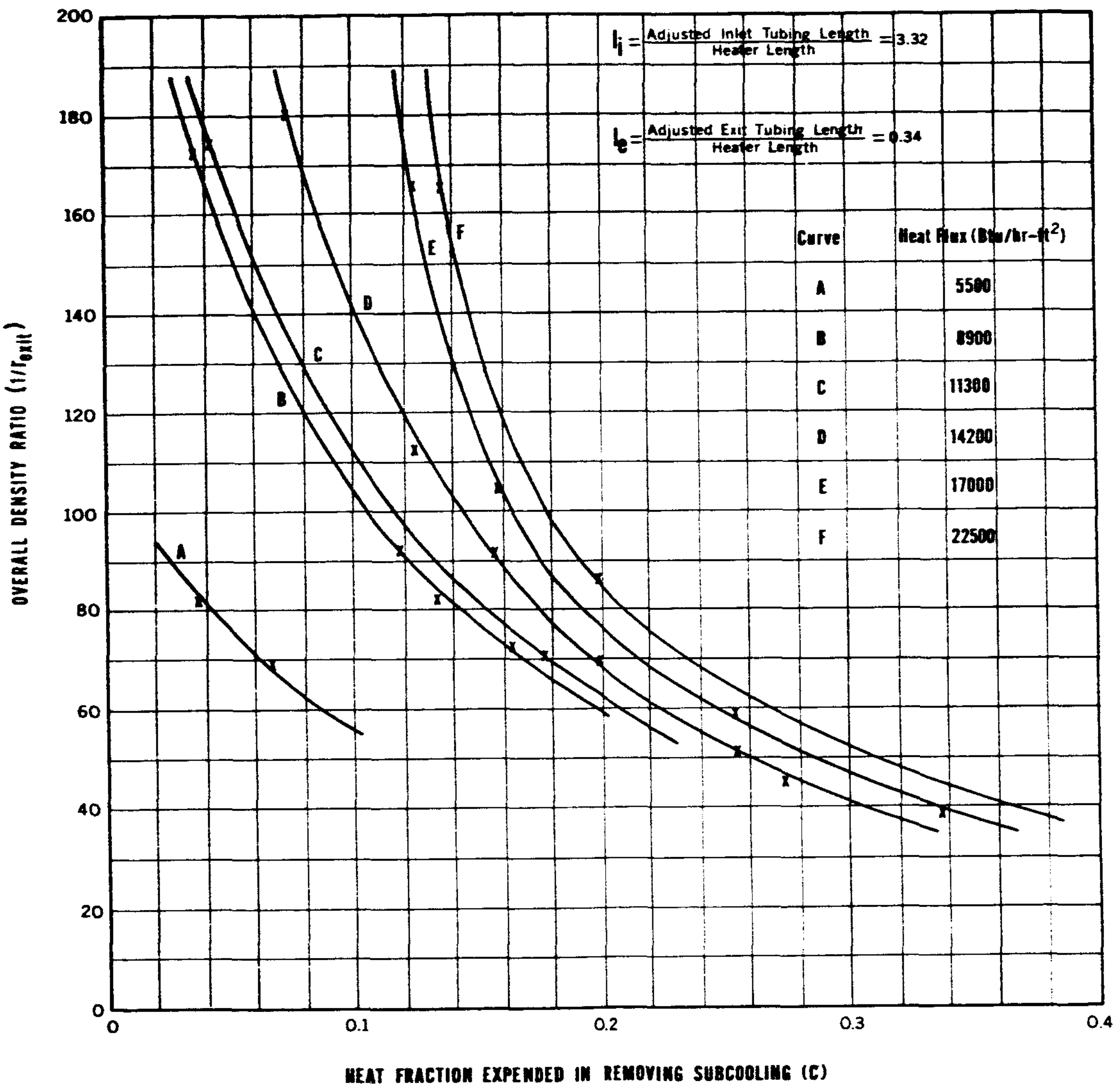


FIG. 3. – OVERALL DENSITY RATIO VS HEAT FRACTION EXPENDED IN REMOVING SUBCOOLING

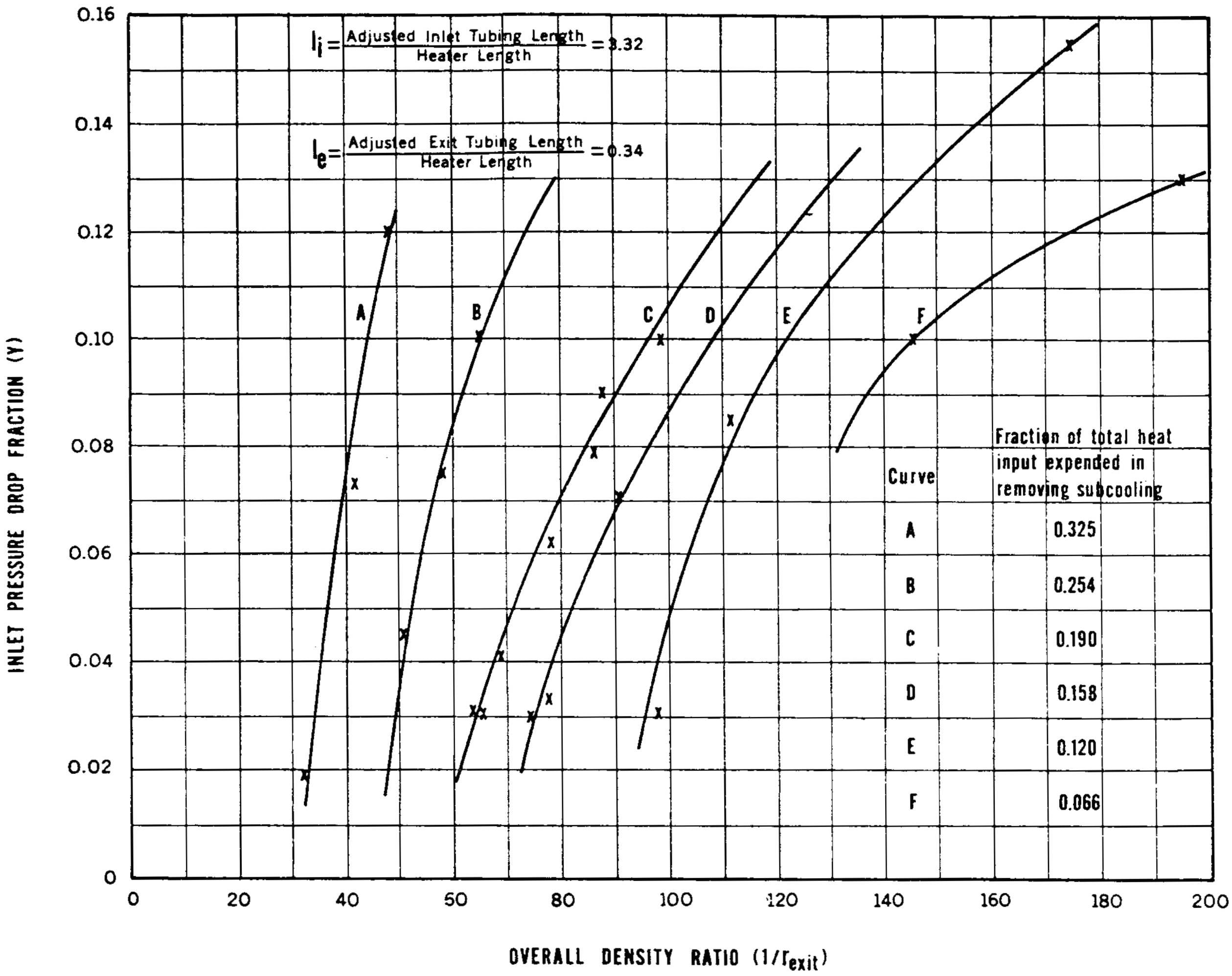


FIG. 4.— INLET PRESSURE DROP FRACTION VS OVERALL DENSITY RATIO

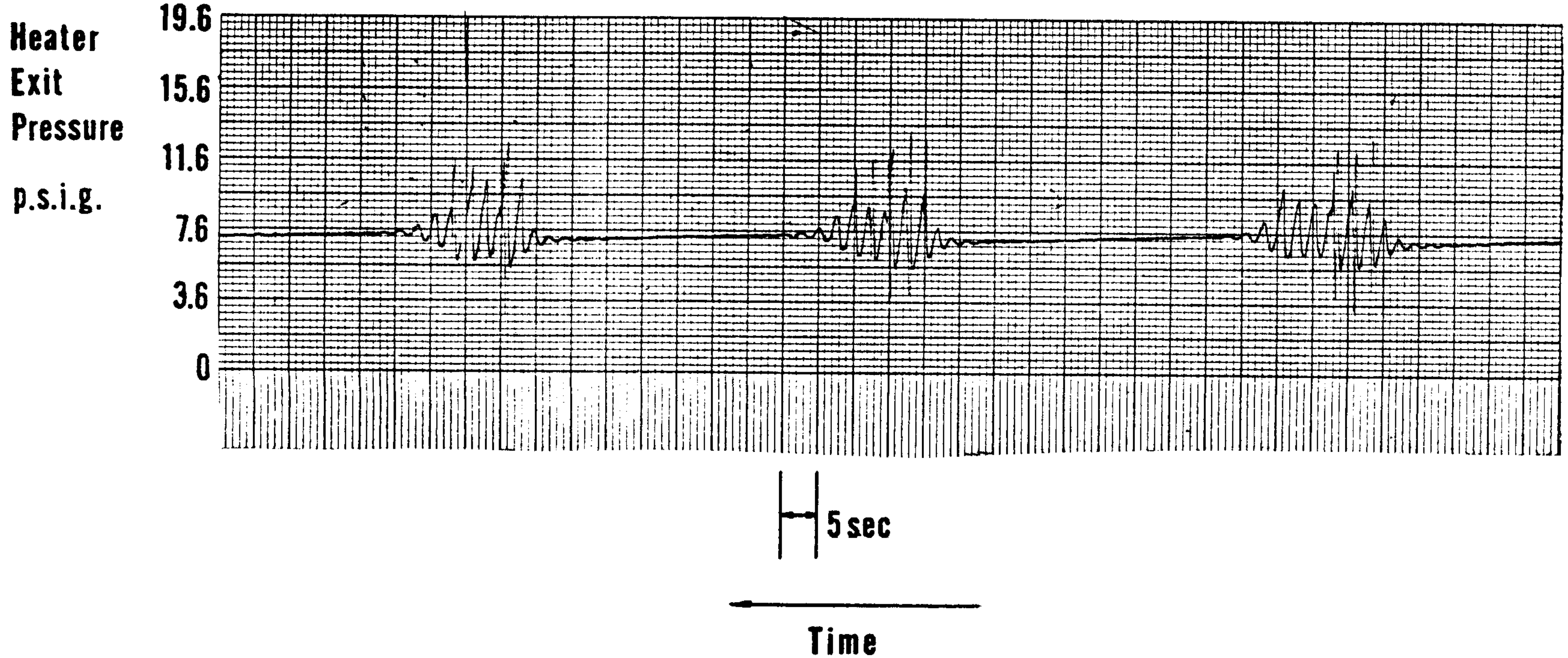


FIG. 5.— A PRESSURE RECORDING OF THERMAL TWO-PHASE FLOW OSCILLATIONS

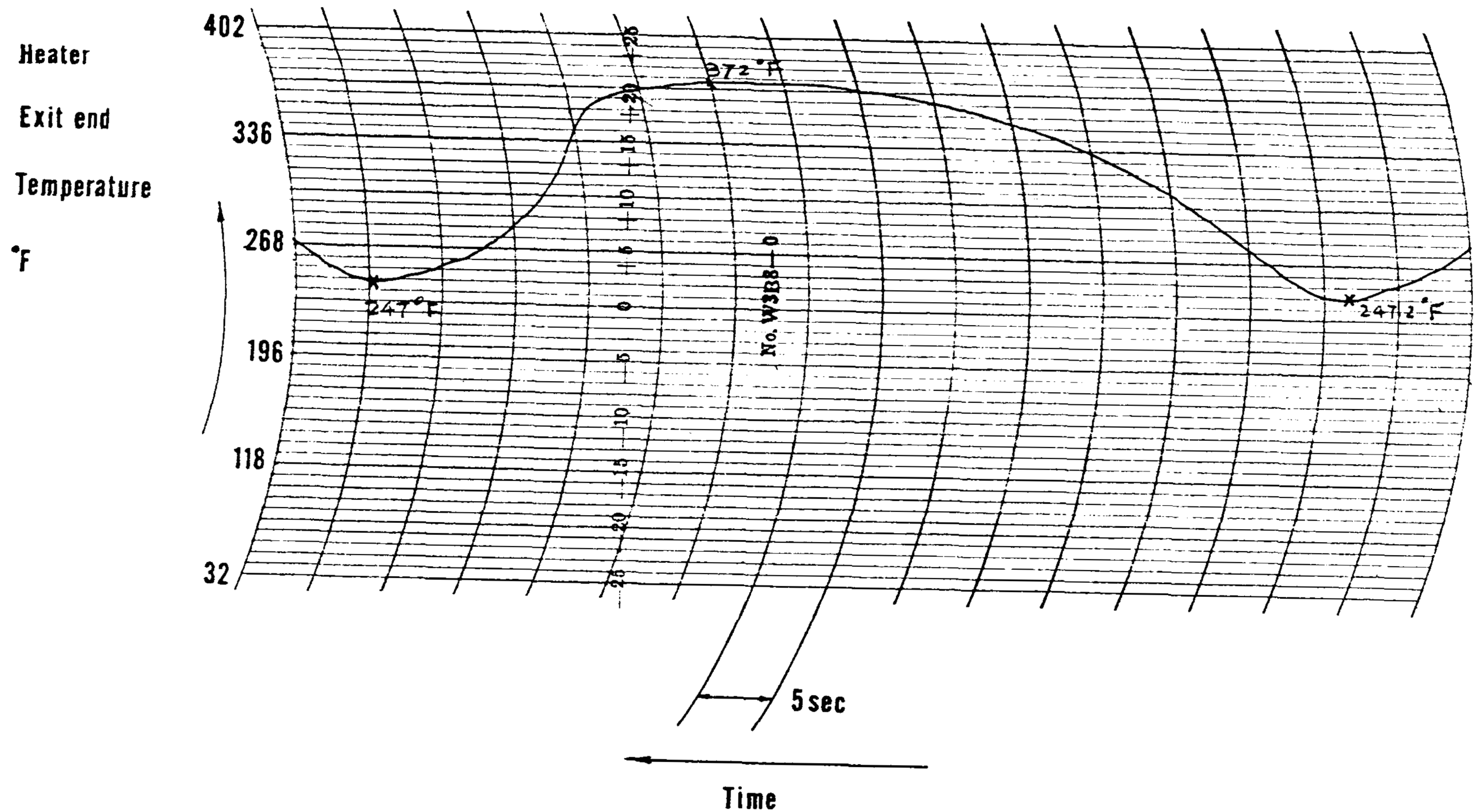


FIG. 6.—A WALL TEMPERATURE RECORDING NEAR EXIT END OF HEATER DURING THERMAL TWO-PHASE FLOW OSCILLATIONS

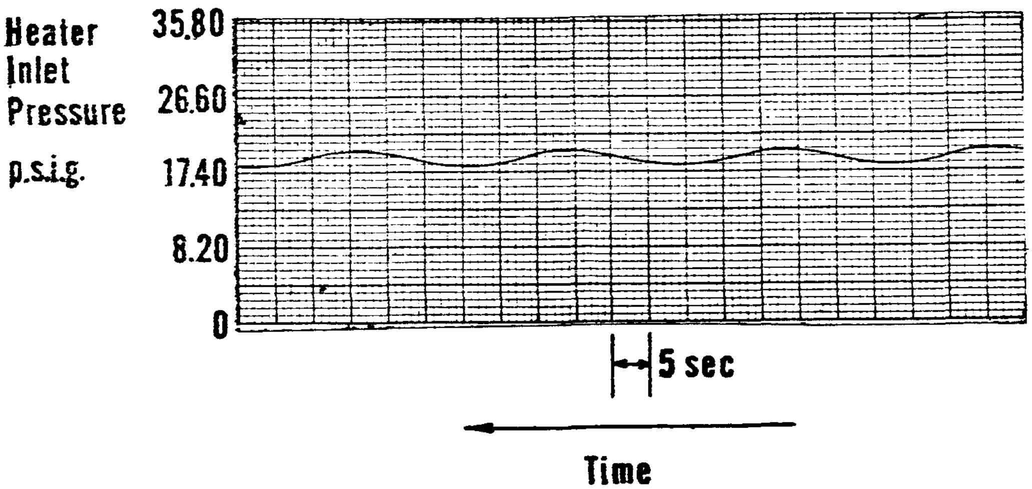


FIG. 7. – A PRESSURE RECORDING OF PRESSURE DROP TWO-PHASE FLOW OSCILLATIONS